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Design and Numerical Modelling of Vertical Axis Helical Wind Turbine for Highway Application

Pradeep Bartaula [a], Shree Raj Shakya [b]

[a, b] *Department of Mechanical Engineering, Pulchowk Campus, IOE, TU, Nepal*
Corresponding Email: [a] 074msmde013.pradeep@pcampus.edu.np, [b] shreerajshakya@ioe.edu.np

Abstract
Though Nepal has a huge potential in the hydro power generation, it hasn't made much exploitation and the power production is very low compared to its production capacity. The current electricity demand of Nepal is around 16641 Mwh whereas present installed power generation capacity is around 15914 Mwh[1]. so, wind energy seems very promising for Nepal to manage the gap between demand and power generation. Little exploitation to extract power from wind has been made only via HAWT. But, use of VAWT can be more promising as they are more beneficial compared to HAWT. This research work is all about the design and numerical modelling of the VAHWT for high power generation on highways. The rotor blades of varying aspect ratio are designed in CATIA V5R20 based on design of WS-0,15B, and simulation was carried out in ANSYS Workbench 18.1 and necessary data are obtained via CFD approach. The data from CFD approach are used for performance evaluation. At the end, when applying CFD approach for evaluation of maximum efficient turbine varying the aspect ratio, has shown the turbine with aspect ratio of 1 to be the most efficient with performance coefficient of 0.3927. Thus, the detail study on this research work has led to the need and opportunity of VAHWT to be further researched and can be developed as a good source of energy producing system. It can also be economical method of power extraction from wind in the countries like Nepal with growing urbanisation.

Keywords
HAWT, CATIA, ANSYS, CFD, Rotor, WS-0 15B, RPM, Performance coefficient

1. Introduction

The study done jointly by Alternative Energy Promotion Centre Nepal, Government of Nepal and Ministry of Environment,Science and Technology found that, at least 3,000 MW of technical wind potential and 448 MW of potential that could be quickly and commercially exploited[2]. The total production of electricity is still below 1000MW while the need of electricity is increasing at exponential rate. Considering the numbers, the annual peak power demand in the fiscal year 2016/2017 was 1559.7 MW, out of which only 855.886 MW was produced indicating huge deficit[3]. To overcome this gap, Nepal should find such resources which can be utilized even in dry season so that there could be optimum production of energy to meet the needs. As Nepal fully relies on hydro power for electricity, the exploration of other resources has yet to be done and many studies show the immense possibilities to generate electricity from various other means such as solar and wind. Nepal has installed only HAWT for the wind power extraction, and VAWT are not being used. Use of VAWT wind turbine can help in more power extraction at low speed and low altitude.

Helical wind turbines have grown in popularity recently especially for home and urban use. Many Helical wind turbines look like DNA structures, large drill bits or other Helical designs which catch the wind and produce electricity. The Helical wind turbine is quieter than bladed turbines because of slower speeds along the blade tips. Another advantage of the Helical wind turbine design is that many times slow minimum wind speeds are needed in order to get the device rotating. Impact winds means the type of wind energy which flows around the moving vehicles due to reaction of body motion. Technically, study of this type of energy is called as Fluid Flow Dynamics.

2. Literature review

A study done by Vinit. V. Bidi and team analyzed the potential of highway power generation using VAWT. The main purpose of the study was to fabricate the turbine at lowest cost possible using the easily available material. The turbine was tested at median of Highways accounting into power generation of 102.4 watts. The turbine rotated at 342rpm at minimum speed of 12.77 m/s[4]. Similar study was carried out by Md Aminul Hassan and Dr. C B Vijaya Vitala. The study was experimented to analyze the potential of energy extraction from wind on highways. The study showed that at a height of 120 cm, the maximum potential of impact wind energy was available[5]. The aspect ratio is one of the important factors to be considered in the design of VAWT. The study carried by S. Bruca, R. Lanzafame and M. Messina analyzed the relation between aspect ratio and performance of the turbine. The study found that turbine with lower aspect ratio had higher power coefficient. An added advantage of greater in-service stability was observed due to structure by having a thicker blade[6].

VAHWT though have been extensively used for small power production purpose, but it is still on research phase rather than commercial use due to its short fatigue life though it can withstand the wind of velocity 35m/s to 40 m/s and maximum up to 60 m/s. Thus, the fabrication of the model of proposed VAHWT is based on the working principle of vertical axis Savonius wind turbine. The model will be fabricated based on the design of VAHWT WS-0,15B produced by Oy Windside Production Ltd, Finland. Different rotor blades with varying aspect ratio is going to design via CATIA V5R20 and they will be imported to the ANSYS Workbench 18.1 for numerical modelling. The data obtained via theoretical and numerical modelling will be analyze and finally numerical modelling will be valided using Benz limit. The main purpose of the project being analysis of the VAHWT, however further analysis will also make varying the aspect ratio of the rotor blade and maximum efficient design will be recommended.

3. Research methodology

The goal of this project is to design and numerical modelling of vertical axis helical wind turbine (VAHWT) suitable for highway application that can generate power under relatively low wind velocities. Different steps that are involved in design, simulation and performance analysis of VAHWT are listed as follows:

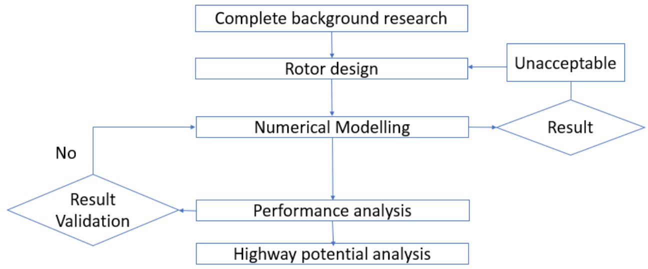

Figure 1: Different steps involved in design and numerical modelling of helical wind turbine

4. Calculations

4.1 Design of 40W vertical axis helical wind turbine

In case of horizontal axis wind turbine, yawing device is necessary for directional mechanism which allow the limited wind direction and large gap between multi turbines. In case of vertical axis wind turbine, the structure needed is simple, less noise level, and suitable for installation in city area due to no restriction of wind direction.

The originality of blade design and dimension was based on the Windside WS-0, 15, wind turbine by Oy Windside Production Ltd-Finland. Slight variation was made because of limitation in methodology of fabrication of blade and tunnel size where it had to be tested. The basic schematic for the aerodynamic design of vertical axis helical wind turbine is shown on figure below.

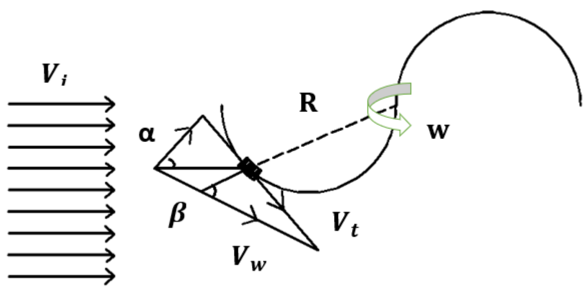

Figure 2: Velocities acting on the vertical axis helical wind turbine

The relative flow velocity and velocity in tangential direction of the vertical axis helical wind turbine are define in below equations.

$$\vec{V_w} = \vec{V_i} \cos\alpha + \vec{V_t} \tag{1}$$

$$V_t = V_i \sin\alpha + wR \tag{2}$$

where,

V_w= Relative flow velocity

V_i = Induced flow velocity

V_t = Velocity in tangential direction

The power in the wind can be computed by using the concepts of kinetics. The wind mill works on the principle of converting kinetic energy of the wind to mechanical energy. The available power in the wind is given by,

$$P_w = \frac{\rho A v^3}{2} \tag{3}$$

And, the rotational speed of turbine and torque can be calculated as

$$N = \frac{\lambda v}{R} \times \frac{60}{2\pi} \tag{4}$$

$$T = \frac{60 \times P_t}{2\pi N} \tag{5}$$

Where,

ρ= Density of air, kg/m3

A= Area of blade, m2

v =Wind velocity, m/sec

λ= Tip speed ratio

T= Torque, Nm

N= Rotational speed, rpm

The tentative dimension of the rotor blades with varying aspect ratio are designed through following assumption.

Table 1: Design parameter of helical blade

Property	Value
Tip Speed ratio	6-7
Coefficient of performance	0.4
Average velocity of vehicle on highways	60 km/hr
Angle of curvature	45
Expected power output	40W
Aspect ratio	Variable

The detailed blade design calculations are as follows:

From considerations, Number of blade (N) = 2

Air density (ρ) = 1.225 kg/m3

Tip speed ratio for 2-bladed turbine (λ) =6

Expected power output (P_o) = 40w

Theoretical power $(P_w) = \frac{P_o}{C_p} = \frac{40}{0.4} = 100W$

For aspect ratio (AR) =1,

As we know that, H=D,

Swept area (A_s) = $H \times D = D^2$

Now,

Theoretical power (P_w) =$\frac{\rho A_s V_o^3}{2}$

Or,100= $\frac{1.225 \times D^2 \times 16.667^3}{2}$

Solving, we get

Diameter and height of rotor with aspect ratio 1 is given by,

D = 18.8 cm and H= 18.8 cm

Similarly, the detail dimension of the blade with different aspect ratio is presented in the table below.

Table 2: Blades dimension

Aspect Ratio (AR)	Diameter (mm)	Height (mm)
0.8	209.8	168
0.9	197.8	178.1
1	188	188
1.1	179	197
1.2	171	205
1.3	165	215
1.4	159	223
1.5	153	230

The detailed design of rotor blade and assembly has been completed in CATIA V5R20 based on the above design parameters and specifications.

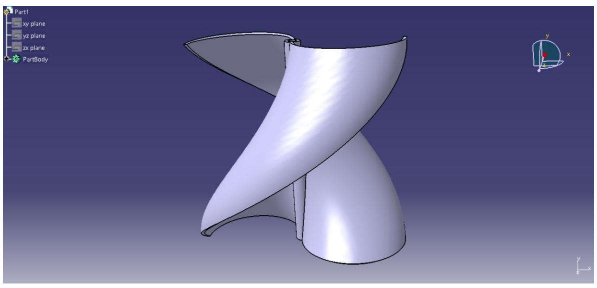

Figure 3: Design of VAHWT in CATIA V5R20

4.2 Design of Shaft

The diameter of shaft couldn't be kept randomly as it has to bear the rotational torque. The design is based on the following assumptions which are tabulated below:

Table 3: Design parameter for shaft design

Property	Value
Max velocity	15 m/s
Factor of safety	5
Max revolution	1500 rpm

Now, based on the above assumptions, calculating the power and tensile strength as:

$Power(P) = \frac{\rho A V^3}{2}$

= 100 W

As, Ultimate tensile strength of ABS Plastic material used in turbine is 46 MPa

So, $P = \frac{2\pi N T}{60}$

Calculating, T = 0.63694 Nm

As we know,

$T \times FOS = \frac{\pi d^3}{16} \times \tau$

Therefore, d = 7.0659 mm

Hence, from above calculation the approximate diameter of the shaft is found to be 7.1mm. During the fabrication, the shaft of 7.1mm dia. is found to be infeasible due to lack of availability of material and machining difficulties. Thus, for the convenience, the diameter of 8 mm has been used for the final model assembly.

4.3 Numerical Modelling

The detailed simulation of rotor was conducted on ANSYS Workbench 18.1 based on several simulation consideration which are tabulated below:

Table 4: Boundary Conditions

Domain
Fluid : Air
Reference Pressure : 1 atm
Blade Material : ABS Plastic
Turbulence Model : SST Model
Inlet Conditions
Air velocity : 5 m/s
Inlet condition : Velocity inlet
Outlet Condition : Pressure outlet
Wall condition : Stationary wall

Number of nodes and elements of rotor with different aspect ratio were calculated and tabulated below:

Table 5: Calculations of different meshing elements

AR	D (mm)	H (mm)	Mesh nodes	Elements	Skewness	orthogonal quality
0.8	209.8	168	367250	2028582	0.847	0.995
0.9	197.8	178.1	372679	2058438	0.843	0.996
1	188	188	381914	2110233	0.799	0.997
1.1	179	197	206476	1132915	0.849	0.995
1.2	171	205	209111	1148055	0.843	0.999
1.3	165	215	385123	2130825	0.846	0.997
1.4	159	223	384855	2129346	0.849	0.995
1.5	153	230	387427	2144365	0.849	0.994

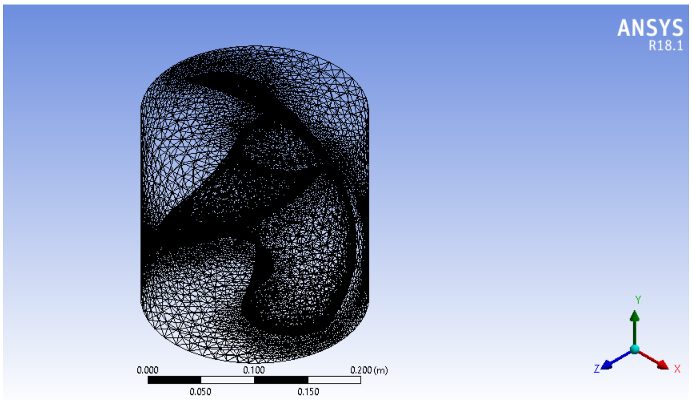

Figure 4: Cylindrical enclosure and rotor with meshing

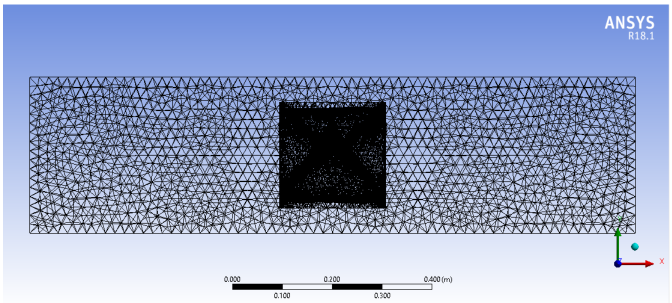

Figure 5: Wind tunnel with meshing

As the geometry of VAHWT is complicated automatic meshing in ANSYS workbench was used resulting in the formation of tetrahedral elements. The meshing process involved the use of both global meshing controls as well as local meshing controls. The local controls used for developing the mesh were face sizing and body sizing.

After complete simulation, torque developed by the turbine rotor was calculated which is used to generate the performance coefficient of rotor. It was found that the rotor with aspect ratio 1 had a maximum performance coefficient of 0.3927. Similarly, the coefficient of performance calculation with different aspect ratio is presented in the table below.

Table 6: Simulation calculations of different blades at 5 m/s

AR	Moment Nm	Moment coeff. Cm	Power output P	Theoretical power Pth	Performance coeff. Cp
0.8	0.0254	0.0016	0.7988	2.6985	0.2960
0.9	0.0237	0.0015	0.7470	2.6971	0.2769
1	0.0338	0.0022	1.0628	2.7060	0.3927
1.1	0.0253	0.0019	0.7973	2.6998	0.2953
1.2	0.0243	0.0016	0.7631	2.6838	0.2843
1.3	0.0237	0.0015	0.7446	2.7160	0.2741
1.4	0.0190	0.0014	0.5991	2.7146	0.2206
1.5	0.0221	0.0016	0.6927	2.6942	0.2571

The below table gives the information about generated torque at different inlet velocity via numerical modelling of the rotor of aspect ratio 1 at 300 rpm. It shows that the inlet velocity of the tunnel is directly proportionate to the torque generated by the rotor blade i.e. the torque generated by the rotor increases sharply with respect to increase in inlet velocity.

Table 7: Torque generated with respect to inlet velocity of blade with aspect ratio 1 at 300 rpm

Velocity(m/s)	Generated Torque (Nm)
5	0.0338
6	0.0372
7	0.0547
8	0.0739
9	0.0905
10	0.108

The below table illustrates about generated torque at different rotational speed of rotor via numerical modelling of the rotor of aspect ratio 1 at 5.8346 m/s i.e. average speed of impact winds energy at sallaghari.

Table 8: Torque generated with respect to RPM of the rotor with aspect ratio 1 at 5.8346 m/s

RPM	Torque generated (Nm)
300	0.0343
350	0.0427
400	0.0481
450	0.0496
500	0.0467
550	0.0449
600	0.0431

4.4 Highway potential analysis

The Highway potential analysis of vertical axis helical wind turbine was carried out at Sallaghari, Bhaktapur because much more advance work has already been done in harnessing the natural wind energy but very much less work has been done in impact energy sector. The noted different wind speed by the help of anemometer at a height of 150 cm with respect to time is tabulated below.

Table 9: Velocity of impact wind energy at sallaghari highway

S.N.	Time	Impact wind energy(m/s)	Average Velocity
1	7:00 AM	4.5	
2	8:00 AM	7.61	
3	9:00 AM	6.73	
4	10:00 AM	7.31	
5	11:00 AM	5.84	
6	12:00 PM	5.1	
7	1:00 PM	5.2	5.834
8	2:00 PM	3.95	
9	3:00 PM	5.4	
10	4:00 PM	7.86	
11	5:00 PM	6.91	
12	6:00 PM	4.42	
13	7:00 PM	5.02	

5. Result and discussion

The data obtained from Numerical modelling on ANSYS Workbench 18.1 and Highway potential analysis at sallaghari are listed as follows:

5.1 Effect in performance coefficient of VAHWT with varying aspect ratio(D/H)

The figure below shows the variation of performance coefficient of vertical axis helical wind turbine with respect to their aspect ratio.

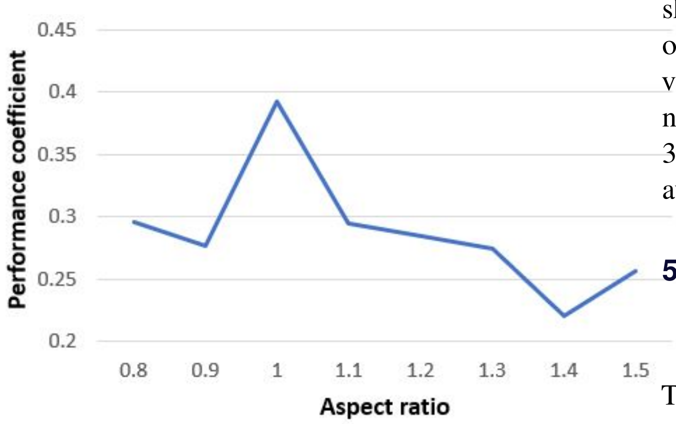

Figure 6: Aspect ratio vs performance coefficient in different models

The data generated from CFD; it can be noticed that the aspect ratio of 1 has a maximum performance coefficient of 0.3927. Thus, the rotor with aspect ratio 1 could be the most economical wind turbine in terms of their power generation and efficiency of the turbine.

5.2 Effect in impact wind energy with respect to time at sallaghari highway

The experiment data carried out, helps to investigate the pattern of impact wind energy available on highways or expressways. For this, the velocity of impact wind energy was carried out to predict the maximum velocity of impact wind energy available at different time throughout the day which is shown in figure below.

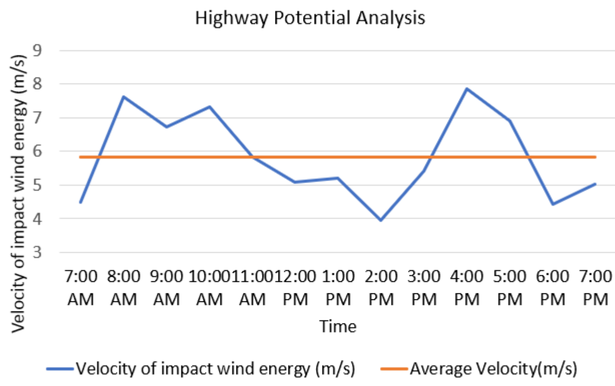

Figure 7: Impact wind energy available at sallaghari highway with respect to time

The experiment data carried out at sallaghari highway shows that the maximum impact wind energy velocity of 7.89 m/s is available at 4 pm due to heavy duty vehicle and more traffic in highways. Also, it was noticed that the lowest impact wind energy is around 3.95 m/s at 2 pm due to less vehicles flow and the average velicity of wind is around 5.8346 m/s.

5.3 Effect in torque generated of helical rotor with varying inlet velocity and rotational speed

The figure gives the information about the torque generated by the blade with aspect ratio 1 with respect to different wind speed at 300 rpm. It shows that the torque generated by the rotor blade is directly proportionate to the impact velocity of wind. Firstly, the torque generated is slightly increased from 5 to 6 m/s due to the rpm of the blade is near to 300 rpm. After that, the torque generated increased sharply due to large variation of rotational speed of the blade.

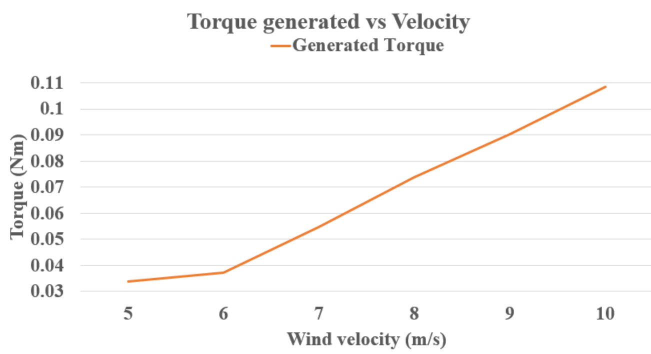

Figure 8: Torque vs inlet velocity of blade with aspect ratio 1 at 300 rpm

The below figure illustrates about generated torque at different rotational speed of rotor via numerical modelling of the rotor of aspect ratio 1 at 5.8346 m/s i.e. average speed of impact wind energy at sallaghari. First and foremost, it showed that the generated torque sharply increased with respect to rotational speed, reaching a peak of 0.049661001 Nm at 450 rpm. Later, then decreased due to exceed rpm for the wind speed of 5.8346 m/s.

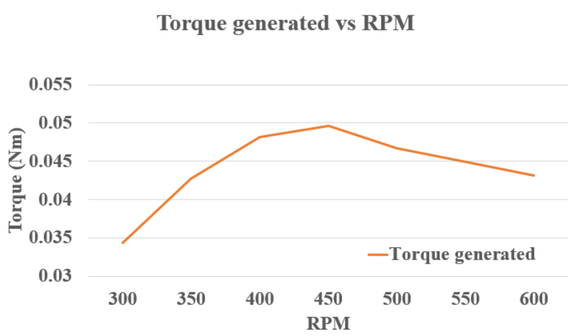

Figure 9: Torque vs rotational speed of blade with aspect ratio 1 at 5.8346 m/s

5.4 Static pressure and velocity distribution on rotor blade with aspect ratio 1

Figure below shows the pressure contour of the rotor blade with aspect ratio 1 at rotational speed of 31.41 rad/s for wind speed 5 m/s. Figure below shows that minimum and maximum static pressure at 5 m/s are -214.2 pa and 29.49 pa respectively.

When the blade is rotating, there is the significant pressure difference in the front side and the rear side of the turbine blade. Due to the helical surface, the pressure difference i.e. force generates the torque.

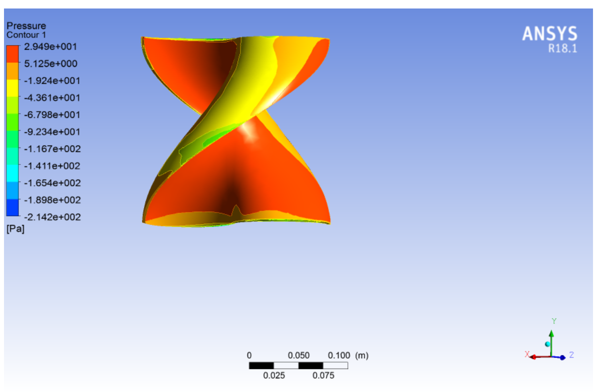

Figure 10: Static pressure contours of rotor with aspect ratio 1

In general, the front side of the blade has higher pressure while the corresponding rear side has a lower pressure. When inflow velocity increases, the pressure difference becomes significant. The pressure difference is large at the blade tip and small at the root. This suggests that significant energy can be extracted near the blade tip. The rear side pressure is negative so the thrust force is transferred to the shaft.

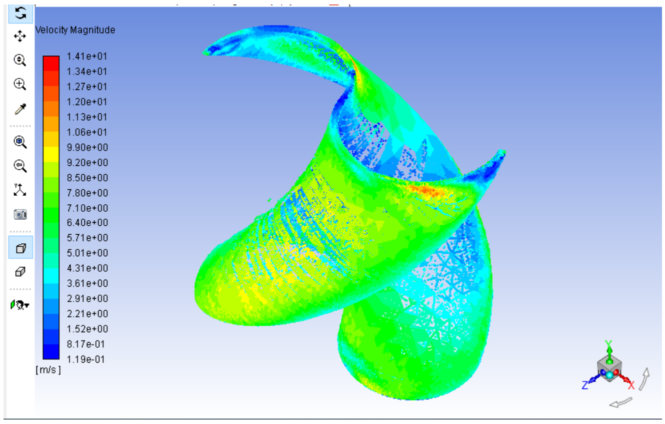

Figure 11: Velocity contours of rotor with aspect ratio 1

Figure above shows the local velocity contour of the rotor blade with aspect ratio 1 at rotational speed of 31.41 rad/s for wind speed 5 m/s.

6. Conclusion

VAHWT is an innovative wind turbine in the sector of wind energy. The design of the rotor of the turbine developed is based on the wind turbine developed by Windside WS-0,15B. Vertical axis helical wind turbines are special types of VAWT with helical structured rotor blade. The different models are designed using several considerations on CATIA V5R20 and they are imported to ANSYS Workbench 18.1 for simulation. After Numerical Modelling on ANSYS Workbench 18.1, the theoretical power and torque were calculated. The coefficient of performance at different aspect ratio was calculated by CFD approach and the maximum coefficient of performance of 0.3927 is found on the rotor with aspect ratio 1. Thus, the turbine with aspect ratio 1 is considered to be the most economical turbine on the basis of power generation as well as its efficiency. The vertical axis helical wind turbine with aspect ratio 1 will be a good source of renewable energy on highways. The impact wind energy generated by the help of moving vehicles on highways can be used to generate electricity which can be stored in a battery and used for different purposes like traffic signals, street lights etc. According to the experimental data collection, the velocity of impact wind energy is around 7.86 m/s as highest at 4 pm which can generate the power of about 3.46 watt by the help of purposed prototype at 446 rpm.

7. Recommendation

The detail study carried out during project work has illustrated that VAHWT has a lot of scope. Thus, detail research can still be carried out to make it more economical and reliable in the field of wind energy. There is a lot of room/space for the further future works as mentioned below. The recommendations for making the VAHWT more efficient and reliable for commercial production are as follows:

1. The angle of curvature of rotor blade can be varied and its effect on performance can be analyzed by both CFD approach and experimental setup.
2. The reference rotational speed of rotor used in simulation section, can be used by experimental method which can give better result and validation.

Acknowledgments

The research work on design and numerical modelling of vertical axis helical wind turbine for highway application has been a great chance for learning and gaining knowledge.The authors of this research would like to pay sincere gratitude to the entire department of Mechanical Engineering, Pulchowk Campus, for their cooperation, coordination and constant support to achieve the goals towards this project.

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